

## Regenerator for a Stirling Engine

5 The present application is a divisional of U.S. application S.N. 09/818,321, filed  
March 27, 2001, Atty Dkt. 2229/122, itself a continuation-in-part of U.S. application  
S.N. 09/517,245, filed March 2, 2000, itself a continuation-in-part application of U.S.  
application S.N. 09/115,383, filed July 14, 1998, and issued May 16, 2000 as U.S. Patent  
no. 6,062,023, and a continuation-in-part also of S.N. 09/115,381, filed July 14, 1998  
and now abandoned, each of which claims priority from U.S. provisional application  
10 number 60/052,535, filed July 15, 1997, all of which applications are herein  
incorporated by reference.

### Technical Field

15 The present invention pertains to regenerators for a Stirling cycle heat engine and  
their manufacture.

### Background of the Invention

Stirling cycle machines, including engines and refrigerators, have a long  
technological heritage, described in detail in Walker, *Stirling Engines*, Oxford  
20 University Press (1980), incorporated herein by reference. The principle underlying the  
Stirling cycle engine is the mechanical realization of the Stirling thermodynamic cycle:  
isovolumetric heating of a gas within a cylinder, isothermal expansion of the gas (during  
which work is performed by driving a piston), isovolumetric cooling, and isothermal  
compression.

25 Additional background regarding aspects of Stirling cycle machines and  
improvements thereto are discussed in Hargreaves, *The Phillips Stirling Engine*  
(Elsevier, Amsterdam, 1991) and in co-pending U.S. patent applications S.N.  
09/115,383, filed July 14, 1998, and S.N. 09/115,381, filed July 14, 1998, which  
reference and both of which applications are herein incorporated by reference.

30 The principle of operation of a Stirling engine is readily described with reference  
to FIGS. 1a-1e, wherein identical numerals are used to identify the same or similar parts.  
Many mechanical layouts of Stirling cycle machines are known in the art, and the  
particular Stirling engine designated generally by numeral **10** is shown merely for  
illustrative purposes. In FIGS. 1a to 1d, piston **12** and a displacer **14** move in phased  
35 reciprocating motion within cylinders **16** which, in some embodiments of the Stirling  
engine, may be a single cylinder. A working fluid contained within cylinders **16** is

constrained by seals from escaping around piston **12** and displacer **14**. The working fluid is chosen for its thermodynamic properties, as discussed in the description below, and is typically helium at a pressure of several atmospheres. The position of displacer **14** governs whether the working fluid is in contact with hot interface **18** or cold interface **20**, corresponding, respectively, to the interfaces at which heat is supplied to and extracted from the working fluid. The supply and extraction of heat is discussed in further detail below. The volume of working fluid governed by the position of the piston **12** is referred to as compression space **22**.

During the first phase of the engine cycle, the starting condition of which is depicted in FIG. 1a, piston **12** compresses the fluid in compression space **22**. The compression occurs at a substantially constant temperature because heat is extracted from the fluid to the ambient environment. The condition of engine **10** after compression is depicted in FIG. 1b. During the second phase of the cycle, displacer **14** moves in the direction of cold interface **20**, with the working fluid displaced from the region of cold interface **20** to the region of hot interface **18**. This phase may be referred to as the transfer phase. At the end of the transfer phase, the fluid is at a higher pressure since the working fluid has been heated at constant volume. The increased pressure is depicted symbolically in FIG. 1c by the reading of pressure gauge **24**.

During the third phase (the expansion stroke) of the engine cycle, the volume of compression space **22** increases as heat is drawn in from outside engine **10**, thereby converting heat to work. In practice, heat is provided to the fluid by means of a heater head **100** (shown in FIG. 2) which is discussed in greater detail in the description below. At the end of the expansion phase, compression space **22** is full of cold fluid, as depicted in FIG. 1d. During the fourth phase of the engine cycle, fluid is transferred from the region of hot interface **18** to the region of cold interface **20** by motion of displacer **14** in the opposing sense. At the end of this second transfer phase, the fluid fills compression space **22** and cold interface **20**, as depicted in FIG. 1a, and is ready for a repetition of the compression phase. The Stirling cycle is depicted in a P-V (pressure-volume) diagram as shown in FIG. 1e.

Additionally, on passing from the region of hot interface **18** to the region of cold interface **20**, the fluid may pass through a regenerator **134** (shown in FIG. 2). Regenerator **134** is a matrix of material having a large ratio of surface area to volume which serves to absorb heat from the fluid when it enters hot from the region of hot interface **18** and to heat the fluid when it passes from the region of cold interface **20**.

Stirling cycle engines have not generally been used in practical applications due to such practical considerations as efficiency, lifetime, and cost, which are addressed by the instant invention.

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### Summary of the Invention

In accordance with preferred embodiments of the present invention, a method is provided for manufacturing a regenerator for a thermal cycle engine. The method includes wrapping a plurality of layers of knitted metal tape in an annular spiral. The knitted metal tape may be wrapped in parallel annular layers around a mandrel and then  
10 the mandrel may be removed. Additionally, the knitted metal tape may be flattened.

In accordance with alternate embodiments of the invention, a method for manufacturing a regenerator for a thermal cycle engine is provided that includes axially compressing a length of knitted metal tube along the tube axis thereby generating a bellows.

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In further embodiments of the invention, a regenerator is provided for a thermal cycle engine. The regenerator has a random network of fibers formed to fill a specified volume and a material for cross-linking the fibers at points of close contact between fibers of the network. The  
fibers may be metal, or, more particularly, steel wool. The material for cross-linking the  
20 fibers may be nickel. The fibers may also be silica glass and the material for cross-linking the fibers may be tetraethylorthosilicate.

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In yet further embodiments of the invention, a regenerator is provided for a thermal cycle engine, where the regenerator has a volume defined by an inner sleeve and an outer sleeve, the inner and outer sleeves being substantially concentric, and two  
parallel planes, each substantially perpendicular to each of the inner and outer sleeves.  
The regenerator also has a random network of fibers contained within the volume, and two screens, each coupled to both the inner and outer sleeves and lying in one of the two parallel planes, such as to contain the random network of fibers within the volume.

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A regenerator for a thermal cycle engine may be manufactured, in accordance with other embodiments of the invention, by filling a form with a random network of electrically conducting fibers, immersing the form in an electroplating solution, and applying a current between the solution and the random network of fibers in such a

manner as to deposit a material for cross-linking the electrically conducting fibers at points of close contact between fibers. Alternatively, a form may be filled with a random network of fibers, whereupon the random network of fibers is sintered in such a manner as to cross-link the fibers at points of close contact between fibers.

5           A further method for manufacturing a regenerator for a thermal cycle engine, in accordance with embodiments of the invention, includes the steps of forming a reticulated foam into a specified shape, depositing a ceramic slurry onto the reticulated foam, heat treating the slurry in such a manner as to burn off the foam, and sintering the ceramic.

10 Brief Description of the Drawings

The invention will be more readily understood by reference to the following description, taken with the accompanying drawings, in which:

FIGS. 1a-1e depict the principle of operation of a prior art Stirling cycle machine;

FIG. 2 shows a side view in cross section of the heater head and combustion chamber of a thermal engine in accordance with a preferred embodiment of the present invention;

FIG. 3a depicts the fabrication of a regenerator by electroplating of a fibrilose starting material in accordance with an embodiment of the present invention;

FIG. **3b** is a cross-sectional of the regenerator chamber of a Stirling cycle engine in accordance with the present invention;

FIG. 4a depicts fabricating a knit-wire wound regenerator in accordance with embodiments of the present invention;

FIG. 4b is a knit-wire tube prior to fabrication into a bellows configuration;

FIG. 4c shows the knit-wire tube of Fig. 4a scored for compression in accordance with an embodiment of the invention;

FIG. 4d shows the knit-wire tube of Fig. 4a scored in an alternative manner for compression in accordance with an embodiment of the invention; and

FIG. 4e shows the knit-wire tube of Fig. 4a after compression to form a bellows  
30 regenerator in accordance with an embodiment of the invention.

### Detailed Description of Preferred Embodiments

Referring to Fig. 2, a cross-sectional view is shown of the expansion volume **98** of a thermal cycle engine, shown for illustrative purposes as a Stirling cycle engine designated generally by numeral **96**, and of the corresponding thermal control structures. Heater head **100** is substantially a cylinder having one closed end **120** (otherwise referred to as the cylinder head) and an open end **118**. Closed end **120** is disposed in a combustion chamber **122** defined by an inner combustor structure **110**. Hot combustion gases in combustion chamber **122** are in direct thermal contact with heater head **100** and thermal energy is transferred by conduction from the combustion gases to the heater head and from the heater head to the working fluid of the thermal engine, typically helium. Other gases such as nitrogen, for example, may be used within the scope of the present invention, with a preferable working fluid having high thermal conductivity and low viscosity. Non-combustible gases are also preferred. Heat is transferred from the combustion gases to the heater head as the combustion gases flow along the outside surface of closed end **120** within a gas flow channel **113**.

Expansion volume **98** is surrounded on its sides by expansion cylinder liner **115**, disposed, in turn, inside heater head **100** and typically supported by the heater head. The expansion piston **121** travels along the interior of expansion cylinder liner **115**. As the expansion piston travels toward closed end **120** of heater head **100**, the working fluid within the heater head is displaced and caused to flow through flow channels defined by the outer surface of the expansion cylinder liner **115** and the inner surface of heater head **100**.

As the working fluid is displaced from expansion cylinder **115** by the expansion piston, working fluid is further heated in passage over the inner pin array **124** and driven through regenerator chamber **132**. A regenerator **134** is used in a Stirling cycle machine, as discussed above, to add and remove heat from the working fluid during different phases of the Stirling cycle. The regenerator used in a Stirling cycle machine must be capable of high heat transfer rates which typically suggests a high heat transfer area and low flow resistance to the working fluid. Low flow resistance also contributes to the overall efficiency of the engine by reducing the energy required to pump the working fluid. Additionally, regenerator **134** must be fabricated in such a manner as to resist spalling or fragmentation because fragments may be entrained in the working fluid and transported to the compression or expansion cylinders and result in damage to the piston seals.

One regenerator design uses several hundred stacked metal screens While exhibiting a high heat transfer surface, low flow resistance and low spalling, metal screens may suffer the disadvantage that their cutting and handling may generate small metal fragments that must be removed before assembling the regenerator. Additionally, stainless steel woven wire mesh contributes appreciably to the cost of the Stirling cycle engine.

In accordance with an embodiment of the invention, a three dimensional random fiber network, such as stainless steel wool or ceramic fiber, for example, may be used as the regenerator, as now described with reference to Fig. 3a. Stainless steel wool regenerator **200** advantageously provides a large surface area to volume ratio, thereby providing favorable heat transfer rates at low fluid flow friction in a compact form. Additionally, cumbersome manufacturing steps of cutting, cleaning and assembling large numbers of screens are advantageously eliminated. The low mechanical strength of steel wool and the tendency of steel wool to spall may both be overcome as now described. In accordance with an embodiment of the invention, the individual steel wires **202**, **204** are "cross-linked" into a unitary 3D wire matrix.

The starting material for the regenerator may be fibrilose and of random fiber form such as either steel or nickel wool. The composition of the fiber may be a glass or a ceramic or a metal such as steel, copper, or other high temperature materials. The diameter of the fiber is preferably in the range from 10 micrometers to 1 millimeter depending on the size of the regenerator and the properties of the metal. The starting material is placed into a form corresponding to the final shape of the regenerator which is depicted in cross-section in Fig. 3b. Inner canister cylindrical wall **220**, outer canister cylindrical wall **222**, and regenerator network **200** are shown. The density of the regenerator is controlled by the amount of starting material placed in the form. The form may be porous to allow fluids to pass through the form.

In an alternate embodiment of the invention, unsintered steel wool is employed as regenerator network **200**. Regenerator network **200** is then retained within the regenerator canister by regenerator retaining screens **224** or other filter, thereby comprising a "basket" which may advantageously capture steel wool fragments.

In one embodiment of the invention, applicable to starting material that is electrically conducting, the starting material is placed in a porous form and placed in an electrolyte bath. The starting material may be a metal, such as stainless steel, for example. An electrical connection is made with the starting material thereby forming an electrode. Cross-linking of the individual fibers in the starting material is accomplished by electrically depositing a second material **206** onto the starting material. The selection

of the starting material will depend on such factors as the particular deposition technique chosen and the chemical compatibility of the first and second materials, as known to one of ordinary skill in the electro-chemical art. During deposition, the second material will build up on the starting material and form bridges 208 between the individual fibers of the starting material in places where the individual fibers are in close proximity to each other. The deposition is continued until the bridges have grown to a sufficient size to hold the two individual fibers rigidly in place.

The deposition duration depends on the particular deposition process and is easily determined by one of ordinary skill in the art. After the deposition is completed, the regenerator is removed from the bath and the form and is cleaned.

In another embodiment of the invention, the starting material is placed in a form that may be porous or not. The form containing the starting material is placed in a furnace and is partially sintered into a unitary piece. The selection of the sintering temperature and sintering time is easily determined by one of ordinary skill in the sintering art.

In another embodiment of the invention, the starting material is placed in a porous form. The form containing the starting material is placed in a chemical bath and a second material, such as nickel, is chemically deposited to form bridges between the individual fibers.

In another embodiment of the invention, the starting material is a silica glass fiber which is placed into a porous form. The glass fiber and form is dipped in a solution of tetraethylorthosilicate (TEOS) and ethanol so that the fiber is completely wetted by the solution. The fiber and form are removed from the solution and allowed to drain in a humid atmosphere. The solution will form meniscoidal shapes bridging fibers in close proximity to each other. The humidity of the atmosphere will start the hydrolysis-condensation reaction that converts the TEOS to silica forming a cross link between the two fibers. The fiber and form may be heat treated at a temperature less than 1000°C, most preferably less than 600°C, to remove the reactant products and form a silica bridge between the fibers.

In another embodiment of the invention, a ceramic slurry is deposited onto a reticulated foam having the shape of the regenerator. The slurry is dried on the reticulated foam and heat treated to burn off the foam and sinter the ceramic. The ceramic may be composed of an oxide ceramic such as cordierite, alumina, or zirconia. The composition of the ceramic slurry and the heat treatment profile is easily specified by one of ordinary skill in the ceramic processing art.

In yet other embodiments of the invention, knit or woven wire is employed in fabrication of a regenerator as now described with reference to Fig. 4a. In accordance with these embodiments, knit or woven wire tube **201** is flattened by rollers **202** into tape **204**, in which form it is wound about mandrel **206** into annular layers **208**. Stainless steel is advantageously used for knit wire tube **201** because of its ability to withstand elevated temperature operation, and the diameter of the wire used is typically in the range of 1-2 mils, however other materials and gauges may be used within the scope of the present invention. Alternatively, a plurality, typically 5-10, of the stainless steel wires may be loosely wound into a multi-filament thread prior to knitting into a wire tube. This process advantageously strengthens the resulting tube **201**. When mandrel **206** is removed, annular assembly **210** may be used as a regenerator in a thermal cycle engine.

Still another embodiment of the invention is now described with reference to Figs. 4b-4e. Knit or woven wire tube **201**, shown in its right cylindrical form in Fig. 4b, is shown scored and partially compressed in Fig. 4c. Alternatively, the scoring may be at an angle **214** with respect to the central axis **212** of the tube, as shown in Fig. 4d. Tube **201** is then axially compressed along central axis **212** to form the bellows form **216** shown in Fig. 4e that is then disposed as a regenerator within the regenerator volume **132** (shown in Fig. 2) of a Stirling cycle engine.

The devices and methods described herein may be applied in other applications besides the Stirling engine in terms of which the invention has been described. The described embodiments of the invention are intended to be merely exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims.